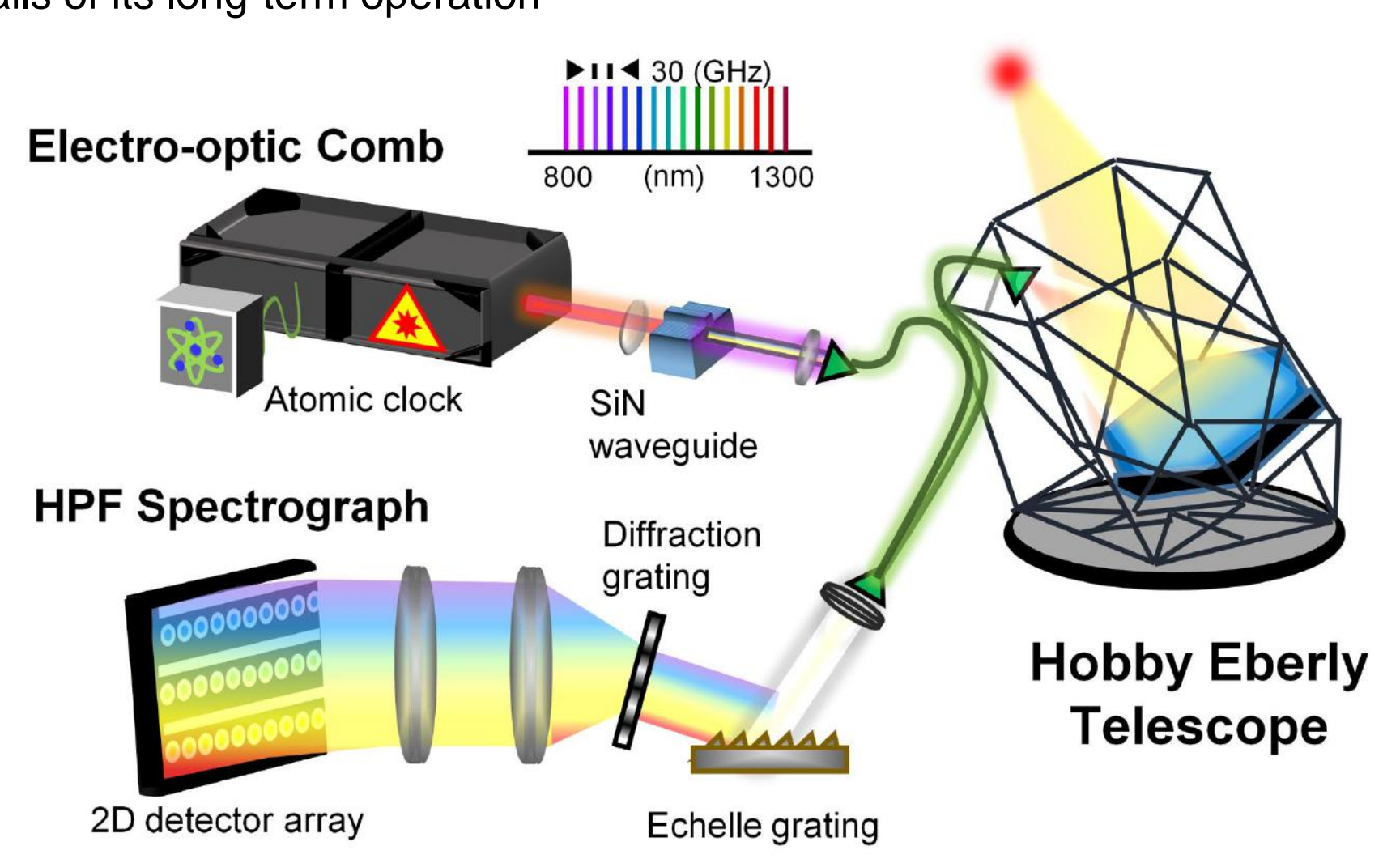


Near Infrared Radial Velocity Calibration

- We have constructed and installed a laser frequency comb (LFC) calibrator for the Penn State Habitable Zone Planet Finger (HPF) at the Hobby-Eberly telescope
- The LFC has now been running continuously for over two years. Here we provide details of its long-term operation



Electro-optic Comb

Atomic clock

SiN waveguide

HPF Spectrograph

2D detector array

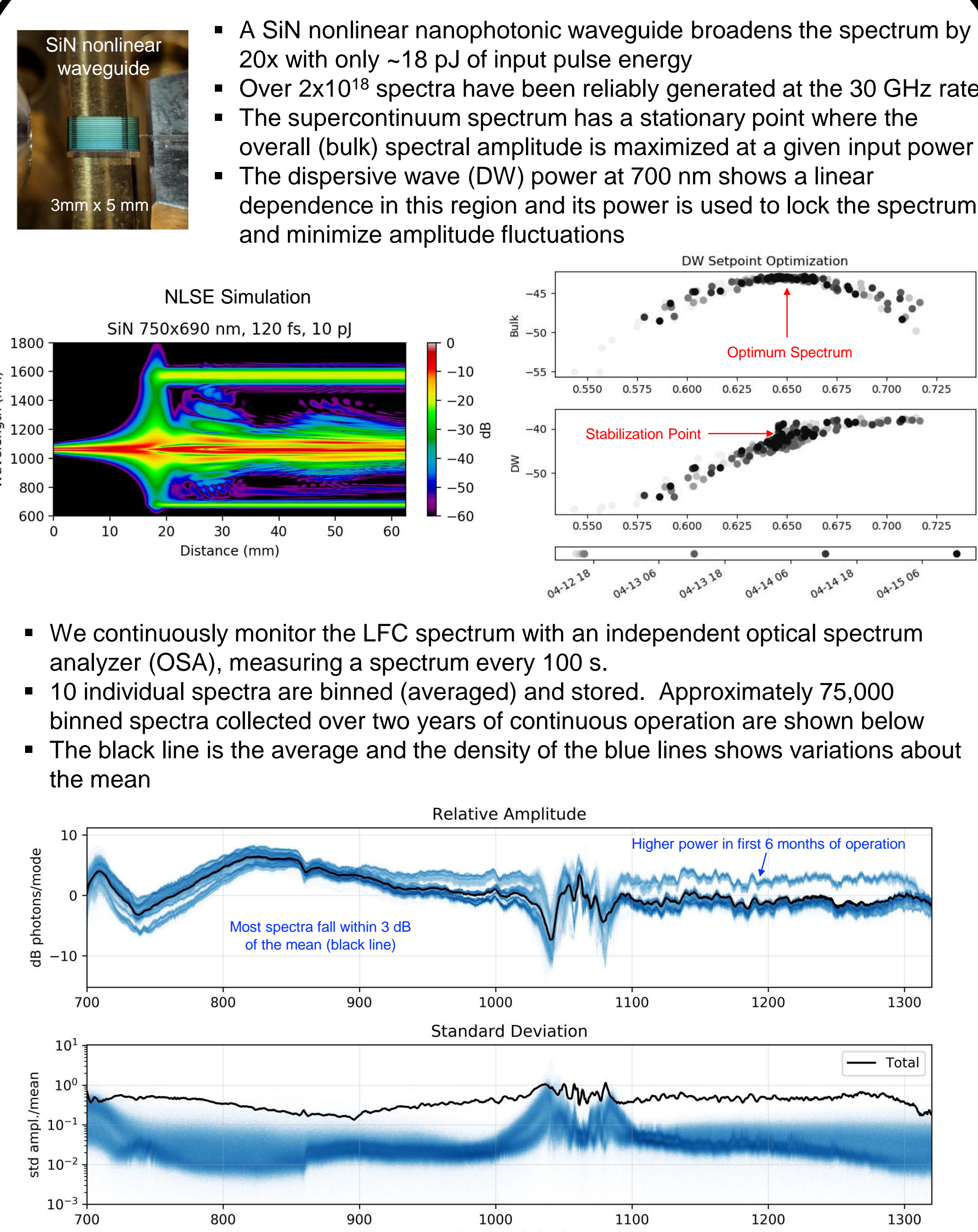
Echelle grating

Hobby Eberly Telescope

Frequency comb bandwidth: **700-1600 nm**
On-sky RV precision with HPF: **~1.5 m/s**
Intrinsic calibration uncertainty with HPF: **<10 cm/s**

Stable and Reliable Supercontinuum

- A SiN nonlinear nanophotonic waveguide broadens the spectrum by 20x with only ~18 pJ of input pulse energy
- Over 2x10¹⁸ spectra have been reliably generated at the 30 GHz rate
- The supercontinuum spectrum has a stationary point where the overall (bulk) spectral amplitude is maximized at a given input power
- The dispersive wave (DW) power at 700 nm shows a linear dependence in this region and its power is used to lock the spectrum and minimize amplitude fluctuations



SiN nonlinear waveguide

3mm x 5 mm

NLSE Simulation

SIN 750x690 nm, 120 fs, 10 pJ

DW Setpoint Optimization

Optimum Spectrum

Stabilization Point

Relative Amplitude

Higher power in first 6 months of operation

Most spectra fall within 3 dB of the mean (black line)

Standard Deviation

Total

- We continuously monitor the LFC spectrum with an independent optical spectrum analyzer (OSA), measuring a spectrum every 100 s.
- 10 individual spectra are binned (averaged) and stored. Approximately 75,000 binned spectra collected over two years of continuous operation are shown below
- The black line is the average and the density of the blue lines shows variations about the mean

- In the lower plot, the black line is the normalized standard deviation of all data
- The blue traces are the normalized standard deviation of 10 binned spectra, showing that the spectral amplitude fluctuations are in the 1-10% range on a 1000 s timescale

References

Metcalf, Andrew J., et al. "Stellar spectroscopy in the near-infrared with a laser frequency comb," *Optica* 6, 233-239 (2019).

Metcalf, Andrew J., et al. "A 30 GHz electro-optic frequency comb spanning 300 THz in the near infrared and visible," *arXiv:1902.02817* (2018)

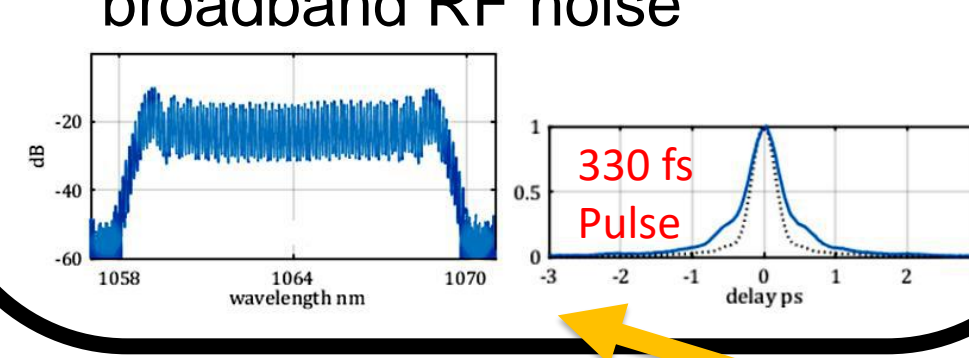
Mahadevan, Suvrath, et al. "The habitable-zone planet finder: a stabilized fiber-fed NIR spectrograph for the Hobby-Eberly Telescope." *Ground-based and Airborne Instrumentation for Astronomy IV*. Vol. 8446. International Society for Optics and Photonics, (2012).

Carlson, David., et al. "Ultrafast electro-optic light with subcycle control," *Science* 361, 1358–1363 (2018).

Funding: NIST-on-a-Chip, NSF AST 1310875; Thanks also to entire HPF collaboration team and Hobby-Eberly staff!

30GHz EOM Comb

- Electro-optic modulators (EOM) convert the continuous wave (CW) laser into a 30GHz comb
 - 10nm of bandwidth
 - Centered at 1064nm
 - 330fs pulse duration
- 1 intensity modulator (IM) and 3 phase modulators (PM)
- Optical filter cavity removes broadband RF noise



330 fs Pulse

30 GHz

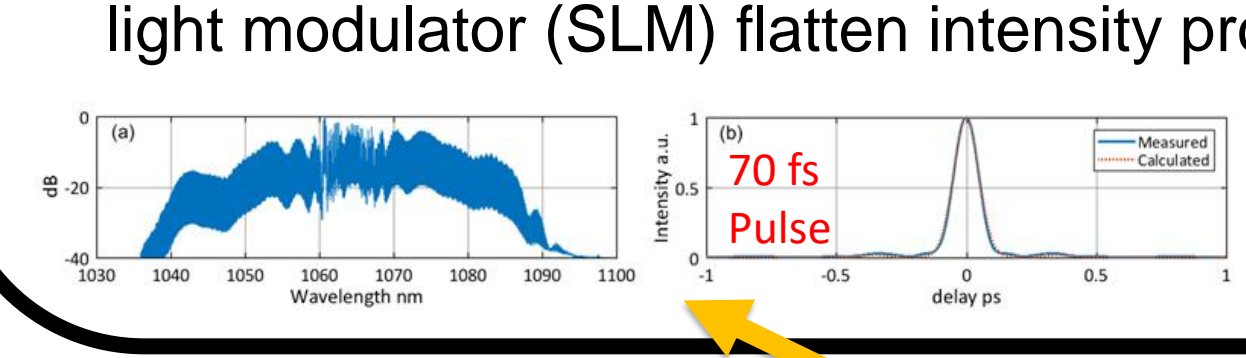
CW Laser 1064nm

Modulators 1 IM, 3 PM

Filter Cavity 30GHz

Supercontinuum Generation and Spectral Flattening

- 1st Stage Broadening
 - 2W (66pJ) optical power (pulse energy)
 - Normal dispersion highly nonlinear fiber (HNLF)
 - Generate bandwidth for ultrashort pulse
 - ⇒ 70fs pulse duration now possible
- 2nd Stage Broadening
 - 525mW (18pJ) optical power (pulse energy)
 - Anomalous dispersion SiN chip waveguide
 - ⇒ Supercontinuum from 700nm to 1600nm
- Combination of static optical filter and spatial light modulator (SLM) flatten intensity profile



70 fs Pulse

Broadening Stage 1

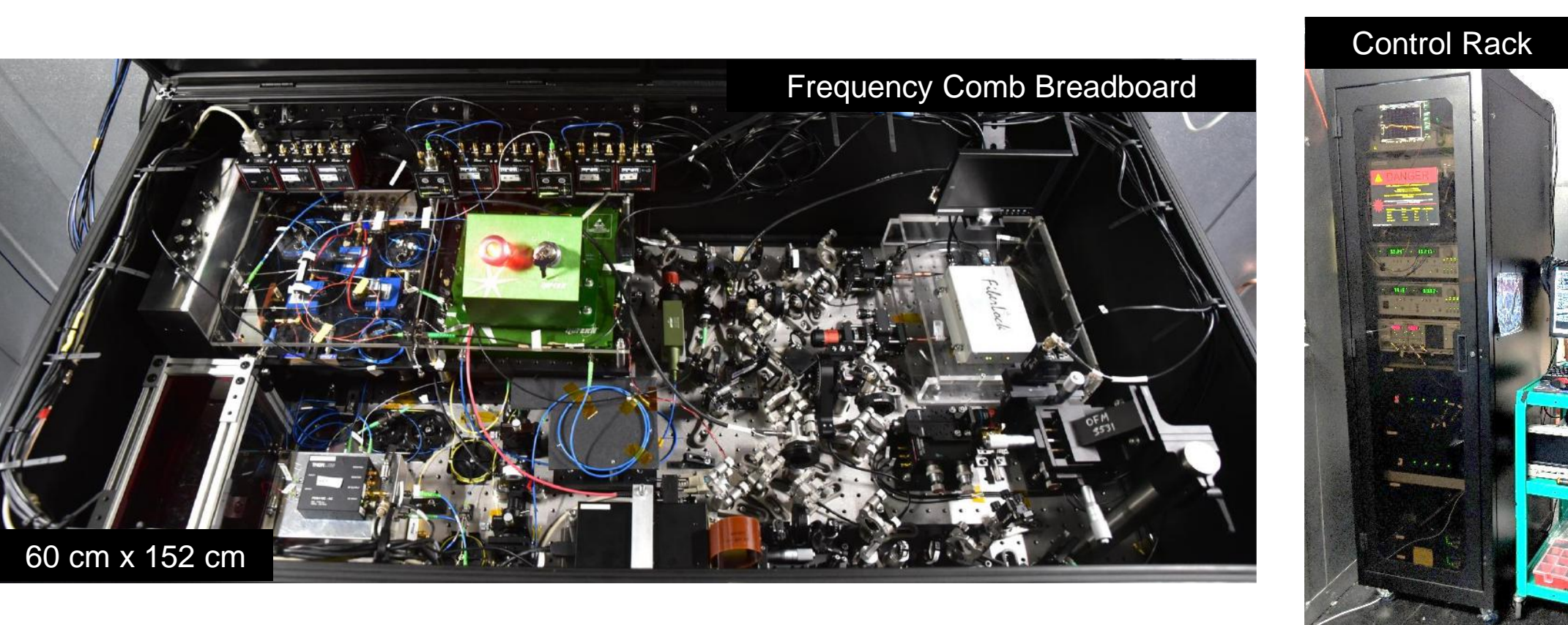
Broadening Stage 2

Spectral Flattening

To HPF

Autonomous Frequency Comb

- The comb has been running autonomously at McDonald Observatory since May 2018
- Built on robust fiber-integrated electro-optic modulator technology
- The entire comb fits on a 2' x 5' optical breadboard
- Power supplies and control electronics fit in a standard electronics rack
- Control software automates the upkeep of the comb and interfaces with the HPF

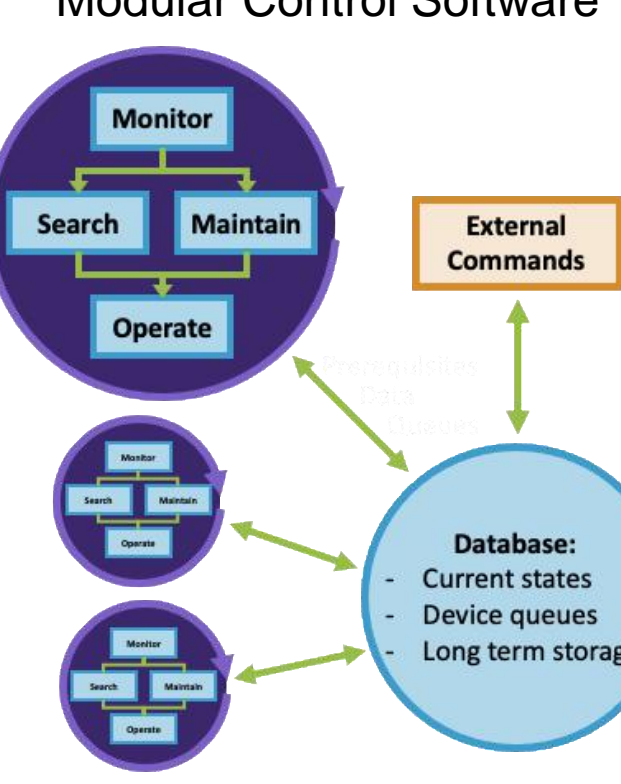


Frequency Comb Breadboard

60 cm x 152 cm

Control Rack

Modular Control Software



Monitor

Search

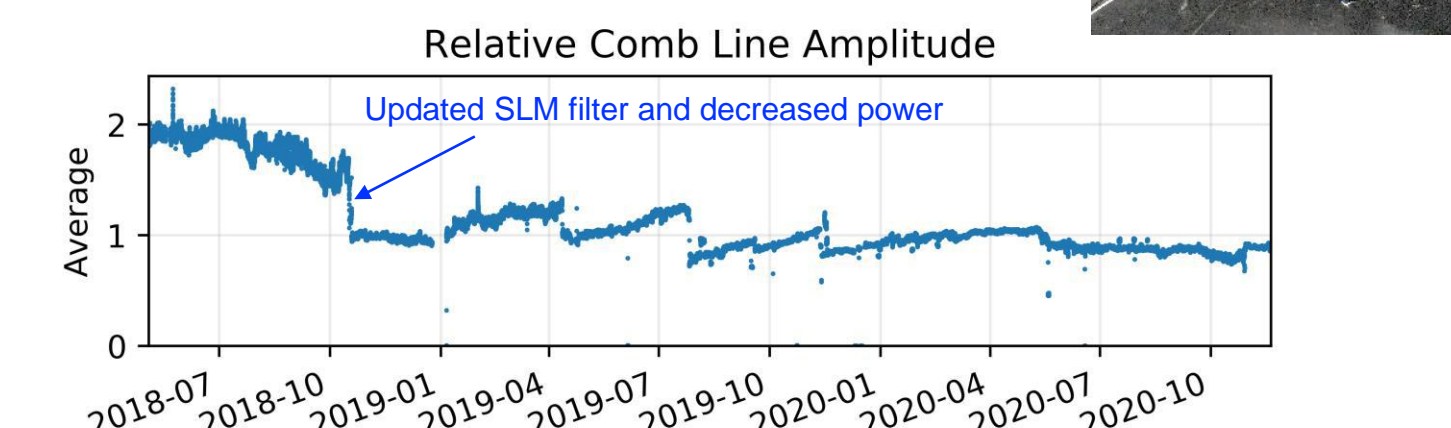
Maintain

Operate

External Commands

Database: Current states, Device queues, Long term storage

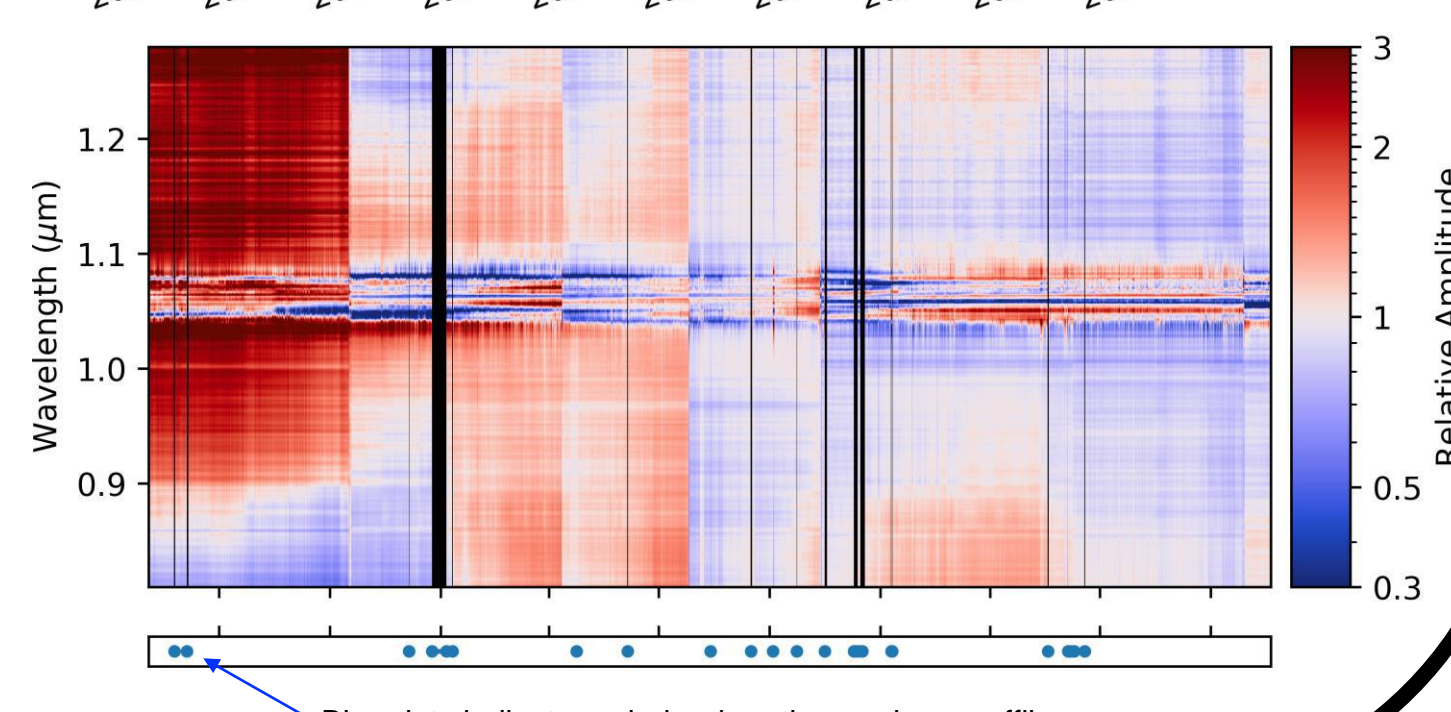
Relative Comb Line Amplitude



Updated SLM filter and decreased power

Average

Blue dots indicate periods when the comb was offline



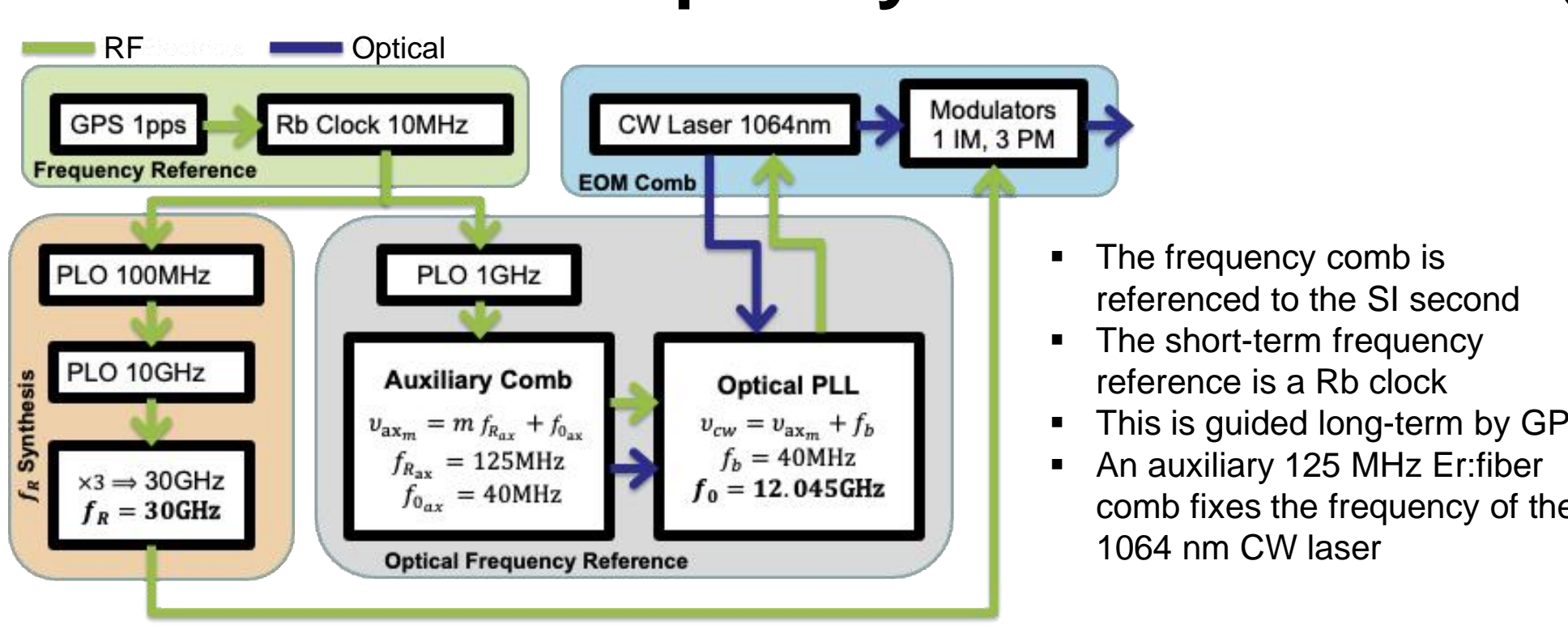
Wavelength (μm)

Relative Amplitude

Overall uptime: **97%**

Absolute Frequency Stabilization

- The frequency comb is referenced to the SI second
- The short-term frequency reference is an Rb clock
- This is guided long-term by GPS
- An auxiliary 125 MHz Er:fiber comb fixes the frequency of the 1064 nm CW laser



RF

Optical

GPS 1pps

Rb Clock 10MHz

CW Laser 1064nm

Modulators 1 IM, 3 PM

Frequency Reference

EOM Comb

PLO 100MHz

PLO 10GHz

f_n Synthesis

$\times 3 \Rightarrow 30\text{GHz}$

$f_R = 30\text{GHz}$

Auxiliary Comb

$\nu_{aux} = m f_{aux} + f_{aux}$

$f_{aux} = 125\text{MHz}$

$f_{aux} = 40\text{MHz}$

Optical PLL

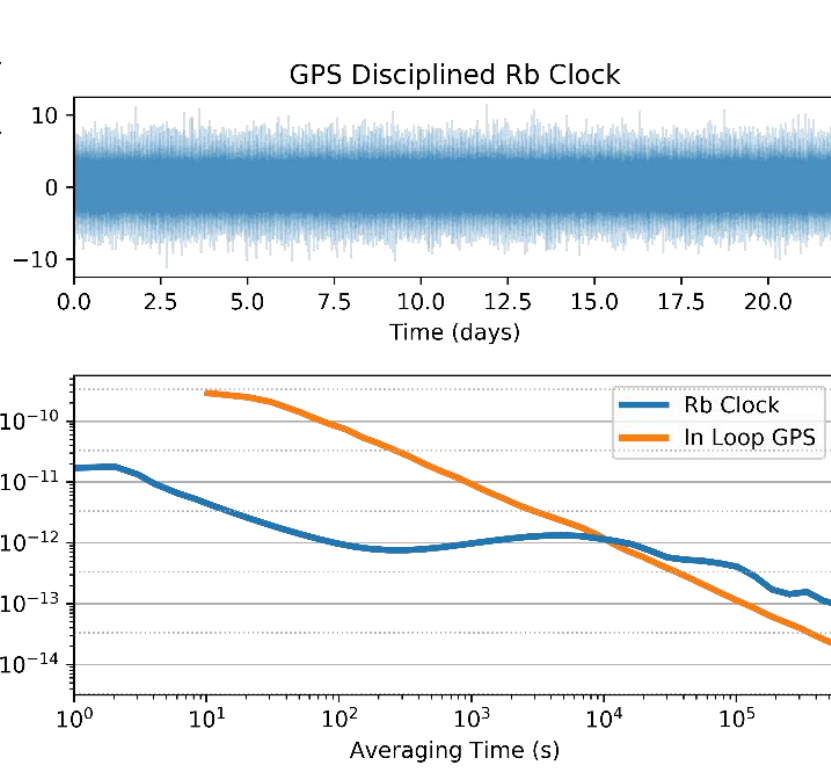
$\nu_{out} = \nu_{aux} + f_0$

$f_0 = 40\text{MHz}$

$f_0 = 12.045\text{GHz}$

Optical Frequency Reference

Laboratory characterization of the GPS-guided Rb clock via comparison to a NIST H-maser



GPS Disciplined Rb Clock

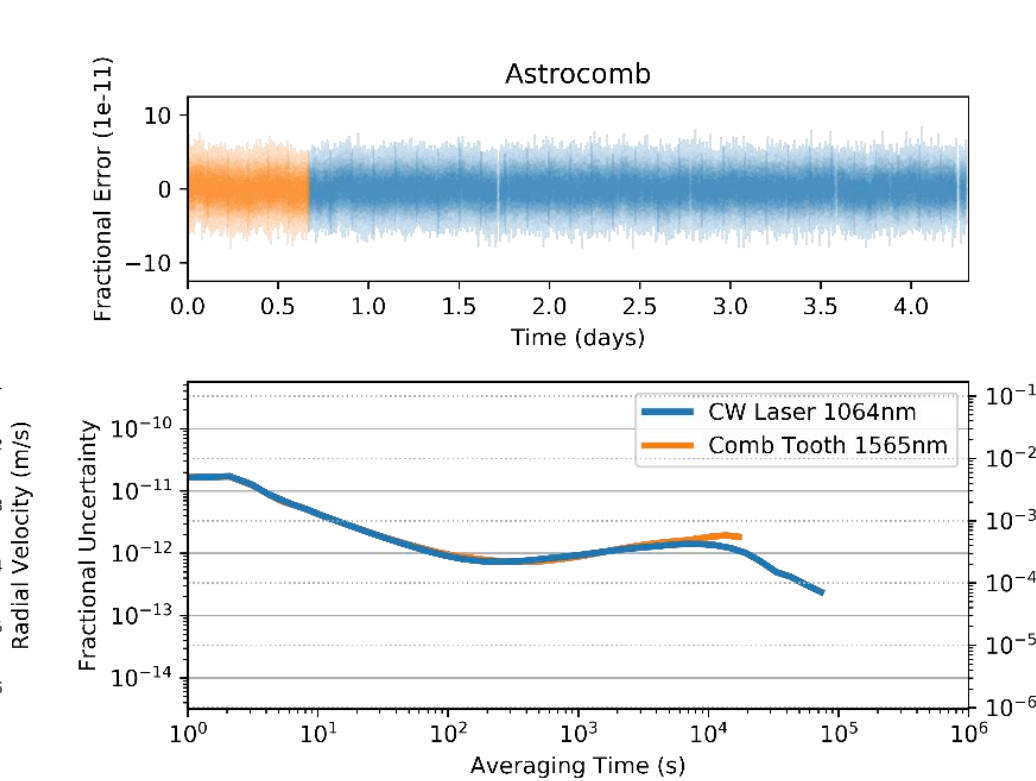
Fractional Error (1σ-11)

Time (days)

Fractional Uncertainty

Averaging Time (s)

Independent measurements of comb line frequencies. The equivalent RV uncertainty is <1mm/s for averaging times >20 s



Astrocomb

Fractional Error (1σ-11)

Time (days)

Fractional Uncertainty

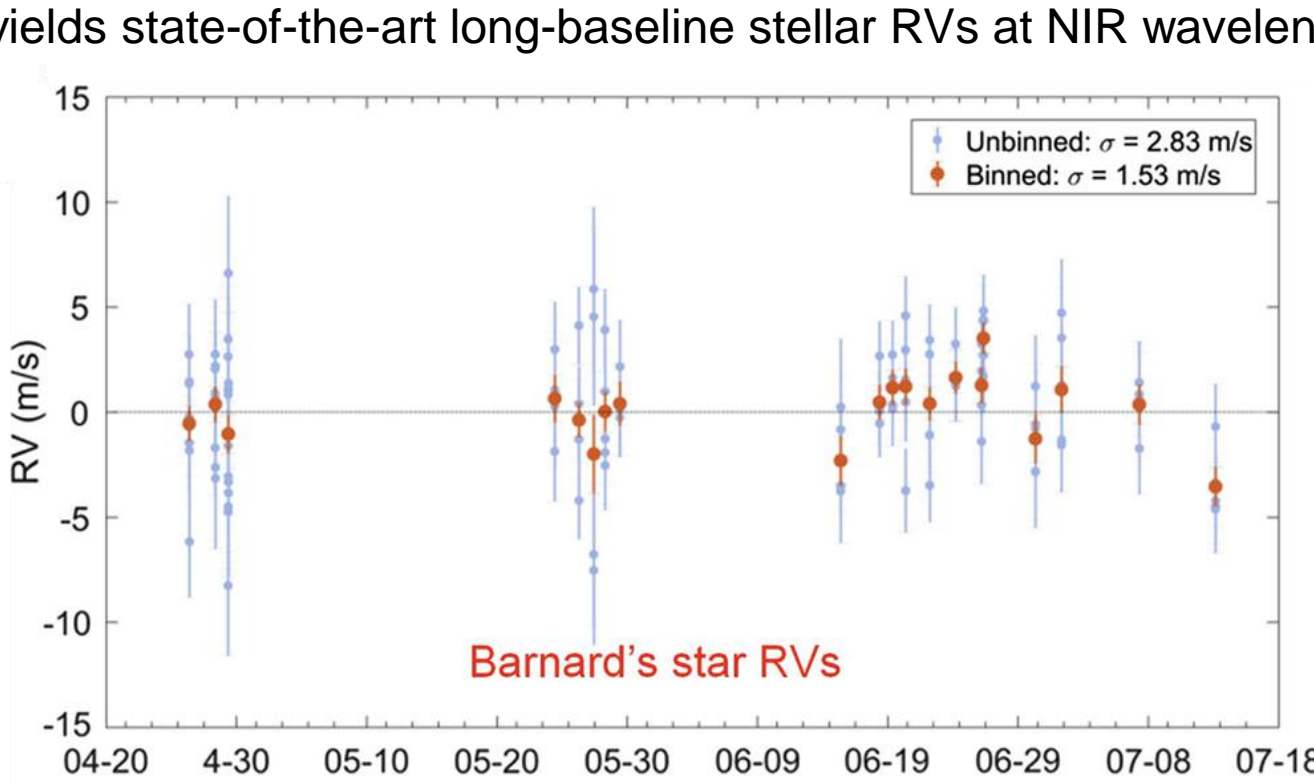
Averaging Time (s)

CW Laser 1064nm

Comb Tooth 1565nm

Enabling Tool for NIR Precision RVs

HPF yields state-of-the-art long-baseline stellar RVs at NIR wavelengths



RV (m/s)

Date (mm-dd) 2018

Barnard's star RVs

Unbinned: $\sigma = 2.83$ m/s

Binned: $\sigma = 1.53$ m/s

Multiple new publications, and more results coming.....

The Astronomical Journal, 159:100 (20pp), 2020 March

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<https://doi.org/10.3847/1538-3811/ab8515>

A Sub-Neptune-sized Planet Transiting the M2.5 Dwarf G 9-40: Validation with the Habitable-zone Planet Finder

Guðmundur Stefánsson^{1,2,3,4,5,6,7}, Caleb Caffer^{1,2,3,4}, John Wisniewski⁸, Paul Robertson⁹, Suvrath Mahadevan^{1,2,3,4}, Marissa Maney¹, Shubham Kanodia^{1,2,3}, Corey Beard¹, Chad F. Bender¹, Peter Brunt¹, J. Christopher Cleves¹

The Astronomical Journal, 159:97 (20pp), 2020 May 10

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<https://doi.org/10.3847/1538-3811/ab8559>

Evidence for He I 10830 Å Absorption during the Transit of a Warm Neptune around the M-dwarf GJ 3470 with the Habitable-zone Planet Finder

Joe P. Ninan^{1,2}, Guðmundur Stefánsson^{1,2,3,4,5,6,7}, Suvrath Mahadevan^{1,2,3}, Chad Bender¹, Paul Robertson⁹, Lawrence Ramsey^{1,2}, Ryan Terrien⁴, Jason Walsh^{1,2,3}, Scott A. Diddams^{1,2}, Shubham Kanodia^{1,2,3}, William Cochran¹⁰

The Astronomical Journal, 160:192 (28pp), 2020 October

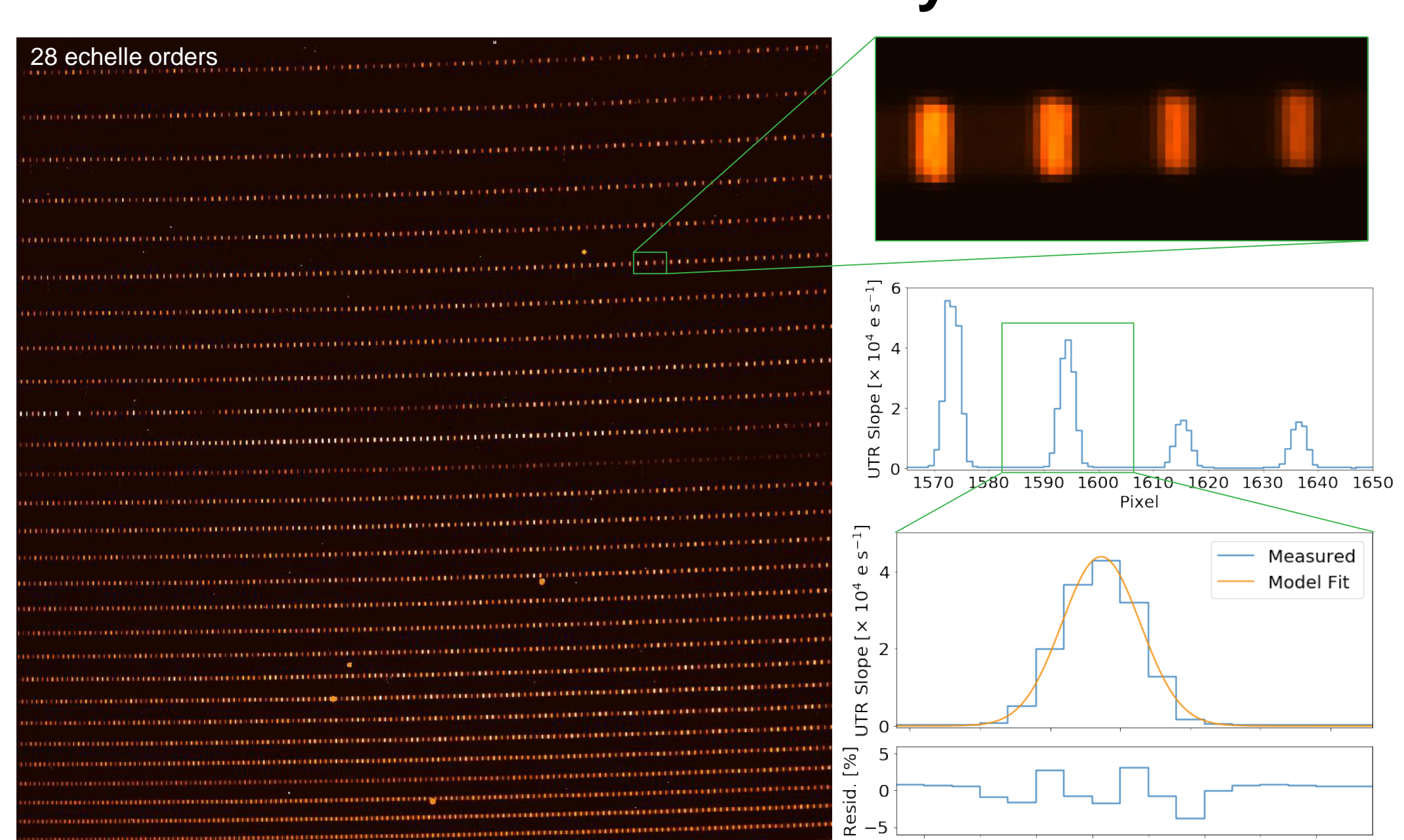
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<https://doi.org/10.3847/1538-3811/ab815a>

The Habitable Zone Planet Finder Reveals a High Mass and Low Obliquity for the Young Neptune K2-25b

Guðmundur Stefánsson^{1,2,3,4,5,6,7}, Suvrath Mahadevan^{1,2,3}, Marissa Maney¹, Joe P. Ninan^{1,2}, Paul Robertson⁹, Jayadev Rajagopal¹, Flynn Haase¹, Lori Allen¹, Eric B. Ford^{10,11}, Joshua Winn¹², Angie Wollgast¹³, Rebekah I. Dawson^{1,2,3}, John Wisniewski⁸, Chad F. Bender¹, Caleb Caffer^{1,2,3}, William Cochran¹⁰, Scott A. Diddams^{10,11}, Connor Fredrick^{10,11}, Samuel Halverson¹², Fred Hearty¹², Leslie Hebb¹³, Shubham Kanodia^{1,2,3}, Eric Levi¹, Andrew J. Metcalf^{10,11,12}, Andrew Monson¹², Lawrence Ramsey^{1,2}, Arpita Roy^{15,12}, Christian Schwab¹⁶, Ryan Terrien¹⁷, and Jason T. Wright¹²

The Comb as Seen by HPF



28 echelle orders

UTR Slope ($\times 10^4$ e⁻¹)

Pixel

Measured

Model Fit

Resid. [%]

Pixel

Image of the LFC spectrum with the HPF's H2RG Detector